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Spacecraft Power Management Software for the New Millennium
Paper Title

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Approved Through January 1970
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TITLE

NM-DS1 SCARLET MANAGER

INNOVATOR(S)

Peter R. GLUCK and Jon SPEER

EMPLOYER

Caltech/JPL

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8. COMMENTS

No additional material is available for a technical support package.

9. PREPARED BY	NAME AND TITLE	SIGNATURE	DATE
Jennifer L. Schlickbernd	Member Technical Staff	Jennifer L. Schlickbernd	6/12/97
10. APPROVED (Center TUO)	NAME	SIGNATURE	DATE
Arif Husain	T.C. Officer	Arif Husain	

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TITLE

NM-DS1 SCARLET PLANNING EXPERT

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APPROVED (After TUO)	NAME	SIGNATURE	DATE
	Arif Husain T.C.C. Officer		

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1. TITLE NM-DS 1 BATTERY MANAGER		
2. INNOVATOR(S) Peter R. GLUCK and Jon SPEER		
3. EMPLOYER Caltech/JPL		4. ADDRESS (Place of performance) 4800 Oak Grove Dr., Pasadena, CA 91109
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		DATE 6/12/97

Spacecraft Power Management Software for the New Millennium

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ABSTRACT

The Jet Propulsion Laboratory's (JPL's) New Millennium Program (NM²) is a **proving** ground for 21st century spacecraft technologies. Chief among these technologies is the field of spacecraft automation. The NM² Deep Space One (DS1) mission will have the most sophisticated autonomous software ever flown on robotic spacecraft. An important element of this software is the Power Management System. Since power is a system resource, this software spans many mission and spacecraft systems. It must predict future spacecraft power generation, plan activities within expected power resources, query on-board navigation and attitude control systems for position and attitude information (which impact solar power generation), monitor and analyze power system state and health, and diagnose and respond to power system failures and emergencies. This paper describes the DS1 Power Management System and its role in the DS1 autonomy software.

TRADITIONAL POWER MANAGEMENT

Since the first spacecraft were launched in the 1950's, spacecraft power systems have existed and so has the need to manage them. The first power systems consisted only of a primary battery. Soon afterward, photovoltaic systems were developed, which gave spacecraft much longer useful lives. For most orbits, relying on solar insolation for primary power also meant having a power storage system, usually containing secondary (rechargeable) batteries.

As spacecraft evolved in complexity, so did the complexity of managing the power system. More payloads and multiple mission goals necessitated careful planning of power consumption and power resources. Dependence on solar insolation added the need for predicting eclipses. Management of nighttime loads required not only preventing exhaustion of the stored energy, but maintaining the battery's health to satisfy the mission duration.

To meet these needs, the power system analyst has developed an expansive set of tools and procedures to assist him or her in maintaining the health and performance of the spacecraft. As computer technology has advanced, these tools have increased in complexity and capability, allowing the analyst to tackle more and more difficult tasks.

SPACECRAFT AUTONOMY

Advanced computers have also molted in more capable and advanced spacecraft systems. Attitude control, data handling, and fault protection systems all took advantage of improved processing and resources. For example, JPL's Voyager probe launched in 1976 had 64 kilobytes of RAM and a clock speed of less than 1 megahertz. In comparison, the Deep Space One spacecraft to be launched in 1998 will have 128 megabytes of RAM and a 20 megahertz clock speed. With critically needed capabilities satisfied, attention has shifted to migrating previously manual activities from the ground onto the spacecraft.

Ground activities like navigation and maneuver planning, command planning and sequencing, data summarization, and fault diagnosis and recovery can all potentially be autonomously handled onboard the spacecraft. Aside from the obvious cost savings realized by smaller operations staffs, there are additional advantages to placing some of these functions on the spacecraft.

For deep space probes, there can be several hours of delay in round-trip communications between the ground and the spacecraft. Onboard fault diagnosis and recovery software can detect, identify, and remedy spacecraft faults, both minor and critical, in a matter of minutes, possibly saving the mission in the process. Summarizing spacecraft health and science data onboard can save valuable downlink bandwidth by transmitting **only the interesting information**. The **ability to plan spacecraft activities onboard allows the spacecraft to respond to major instrument failures or other anomalies without impacting the remaining healthy spacecraft systems and investigations**. In the event of a

major anomaly, the spacecraft can respond quickly and generate a new sequence of commands to carry out the remaining possible mission objectives.

The Deep Space One flight software will contain all of the above elements. It is quite probably the most advanced spacecraft software ever flown.

Autonomous Power Management

Autonomous power management combines the functions of traditional onboard power management with the functions normally performed by a power system analyst on the ground. Traditional onboard functions include detection and isolation of major power short circuits, calculation and monitoring of battery state-of-charge, and monitoring of power system component temperatures. The power system analyst is normally responsible for command sequence validation, health analysis, and fault diagnosis and recovery [1]. Migrating these functions to the onboard system means teaching the spacecraft processor how to accomplish these tasks.

Of these three analyst responsibilities, command sequence validation is the most important for achieving full spacecraft autonomy. Health analysis and fault diagnosis are already performed onboard many spacecraft to a greater or lesser degree. While these two aspects of the analyst's job are essential, refining them into a fully autonomous spacecraft is merely a process of evolution. Performing command sequence validation onboard, on the other hand, is a heretofore untried technique.

Command Sequence Validation

Command sequence validation is the process whereby the spacecraft analyst confirms that the sequence of commands to be executed will not exceed spacecraft performance limitations and will do what is expected. In particular, the power analyst is concerned with the power system energy balance and the peak system load.

The overall energy balance must be positive or the spacecraft will eventually deplete its batteries, which is usually a major fault condition. To have a positive energy balance, the total energy provided by the solar array over a period of time (anywhere from one orbit to 100 days, depending on the mission) must be greater than the total spacecraft load and battery discharge after all system inefficiencies are accounted for. Furthermore, the peak system power must not exceed the capability of the system to deliver power to the loads. The limiting factor here is usually the size of the relays, fuses, or electrical harness.

In order to check peak power and energy balance constraints, the power analyst will usually follow some variant of the procedure given here:

1. Obtain the command sequence to be validated.
2. Predict the spacecraft load profile (power vs. time) for the sequence.
3. Predict the source power available (power vs. time) during the sequence.
4. Predict battery usage during the sequence.
5. Validate that operational constraints are not violated.

Load Profile Prediction. First the analyst obtains the command sequence to be validated. In the early days it was a hardcopy; today we use electronic files to facilitate data transfer. Next, the analyst will use the command sequence to determine what the spacecraft load profile is during the sequence. For example, whenever a unit is turned on, the load increases. The sum of the power consumed by all operating units is the spacecraft load at a given time, and this value changes with time as equipment is turned on and off. Some assumptions must usually be made about the power consumed by nondeterministic loads like thermostatically controlled heaters. The analyst compensates for these assumptions by maintaining additional margin in the sequence validation criteria. Automation of this step is almost trivial, since most of the problem has already been implemented in ground analysis software.

Source Power Availability Prediction. The third step is to predict the power available from the power source (e.g., a solar array or radioisotope thermoelectric generator--RTG). This power may depend only on age and temperature, as with the RTG, or it may involve additional factors like radiation exposure, spacecraft attitude, anti-radiation to the Sun. Photovoltaic systems, in particular, are sensitive to all of these factors. In this case, predicting the solar array performance can involve detailed knowledge of the spacecraft's position, attitude, temperature, and history.

At first glance, it may appear that this job is entirely too complicated for an onboard algorithm, which must be robust and not overly consume spacecraft processing resources. However, there are some important simplifications which can be made to reduce the complexity of these predictions.

First, and most important, it is essential to have sample cells on the solar arrays. The sample cells should be configured to report the short-circuit current and open-circuit voltage, either continuously or on demand, as well as cell temperature. Note that this information is usually provided anyway so that the ground-based power analyst can perform his or her job adequately. Armed with this in-situ information, a history of the spacecraft and knowledge of its position are no longer required, since it can be safely assumed that the spacecraft's sun-range and the array's performance will not change much over the short and relatively near period for which the sequence is being evaluated.

Temperature is similarly available on-board, and so the only remaining problem is knowing the spacecraft's attitude, or, more specifically, the solar array's attitude relative to the Sun. Here, again, a simplifying assumption can be made. Most spacecraft have an attitude control mode or state which is their "sun-referenced" state, and this is typically where the spacecraft spend most of their time. Off-axis activities are usually short duration where the spacecraft must point in a different direction to, say, line-up the engine along the thrust vector or point an instrument at a target. Once this activity is done, the spacecraft returns to its sun-referenced state. Therefore, for planning purposes, it is usually adequate to assume that when the spacecraft leaves its sun-referenced state there is no solar array power available and the batteries supply the entire load. This is conservative, to be sure, but allows the major simplification of not trying to predict the actual solar array attitude onboard.

So, with the in-situ solar cell sample telemetry and the simple rule that whenever the spacecraft is not sun-referenced the batteries should be used, predicting solar array performance becomes a simple arithmetic exercise easily performed by the spacecraft processor. The solar cell samples, along with some

known parameters like the curve fill factor, are used to generate the present solar cell I-V curve. Once the I-V curve is available, it is simply scaled by the known number of cells to determine the total power generated by the solar array. This value is then multiplied by a transfer efficiency factor (specific to the given power system) to determine the actual power available to the loads and battery.

For Deep Space One, then, the solar array power prediction process will depend on a combination of ground-specified parameters, in-situ measurements and queries to other software subsystems. The onboard navigation software will be queried to provide the spacecraft's position in the solar system, which can be readily transformed into Sun range. The farthest range for the sequence will be used for planning purposes, thus providing a conservative estimate of available power. (We could alternately, as suggested earlier, dispense with knowledge of the spacecraft's position and simply apply some margin, but since position is available onboard we can get a more accurate prediction by using it.)

The Sun range will also be used to determine whether the spacecraft is inbound towards the Sun or outbound away from the Sun. If outbound, the software will use the present solar array temperature as a conservative estimate (the array will only get colder, increasing power output). If inbound, then some temperature margin (specified by the ground as a function of the length and nearness of the command sequence) will be added to the present temperature.

Attitude control software will report the expected spacecraft attitude during the command sequence. This will be used to determine the solar array Sun angle, which in turn will indicate whether the array is sun-pointed or whether battery power will be required. Radiation degradation is already factored into the in-situ solar array measurements. Any needed parameters (like solar cell performance parameters) will be provided by the ground and updated as required. It is expected that these updates will be infrequent, perhaps every six months or so.

Energy Balance Prediction. The fourth step is to predict the spacecraft energy balance during the proposed command sequence. Again, we can take advantage of three decades of work developing ground analysis tools which compute battery discharge and charge performance. These algorithms can simply be transferred to the onboard system. Although these programs are perceived as complex and processor intensive, they will run in a matter of minutes on modern processors.

Finally, now that all of the requisite information is available, the command sequence may be validated. The power load profile is checked to verify that no peak power constraints are violated. If the onboard process determines that the peak power is excessive at any point, it will simply reject the sequence. Similarly, if the energy balance prediction indicates that the battery discharge will be excessive, such that fault protection software would be activated, or that the battery would not get fully recharged within the allowed period, then the sequence would be rejected on those grounds. In either case, the onboard planning software must then modify the sequence so that the peak power problem is alleviated [2]. This will be accomplished by relocating or abandoning lower

priority goals and activities. If the onboard planning software cannot develop a viable command sequence, it must notify ground operations that it is unable to achieve the requested goals.

CONCLUSIONS

All of the above tasks are relatively straightforward, but computationally intensive. They are therefore perfectly suited for computers. In fact, most of this process has been automated in ground systems in recent years, with only portions remaining for the analyst to push the buttons and review the results. Automating these last tasks is the key to moving these functions onto the spacecraft.

Computer technology has now advanced to the level where putting these functions onboard is not only feasible, but practical. The spacecraft is, after all, in the best position to judge its own situation, especially when it takes several hours for a radio message to get to the ground and back. On board planning and sequencing allows the spacecraft to take advantage of the latest, best knowledge of the spacecraft state when generating a command sequence. Better yet, it allows the spacecraft to react to unexpected changes in the spacecraft state (e.g., failures), and try to replan its activities to recover some, if not all, of the mission goals.

Through these higher levels of spacecraft autonomy, we can achieve the vision of fleets of robotic spacecraft exploring the solar system. Directed by only a few, high-level goals, these spacecraft will be able to plan and execute their own command sequences to best achieve the goals requested. The support staff on the ground will be very small, just enough people to receive and evaluate an occasional report from the spacecraft. Autonomous power system management is as essential to this vision as the power system is to the spacecraft itself.

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